Constraints on Long-Range Dark Matter-Standard Model Interactions From Dynamical Friction in Ultrafaint Dwarf Galaxies

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Based on work with Harikrishnan Ramani and Peter Graham

Outline

- Background:
  - Dark Matter and New Interactions
  - Ultrafaint Dwarf Galaxies
  - Dynamical Friction
- Dynamical Friction in Ultrafaint Dwarf Galaxies:
  - Stellar Evolution
  - Constraints on New Interactions

Background

Dark matter can interact with the Standard Model through weak, long-ranged forces

Strengths Relative to Gravity (for **S**tandard Model/**D**ark Matter)

Masses (for Standard Model/Dark Matter)

Force Range

$$F \sim \pm \underbrace{\sqrt{\alpha_{SS}\alpha_{DD}}}_{\alpha_{SD}} \frac{m_{SM} m_{DM}}{r^2} e^{-r/\lambda}$$

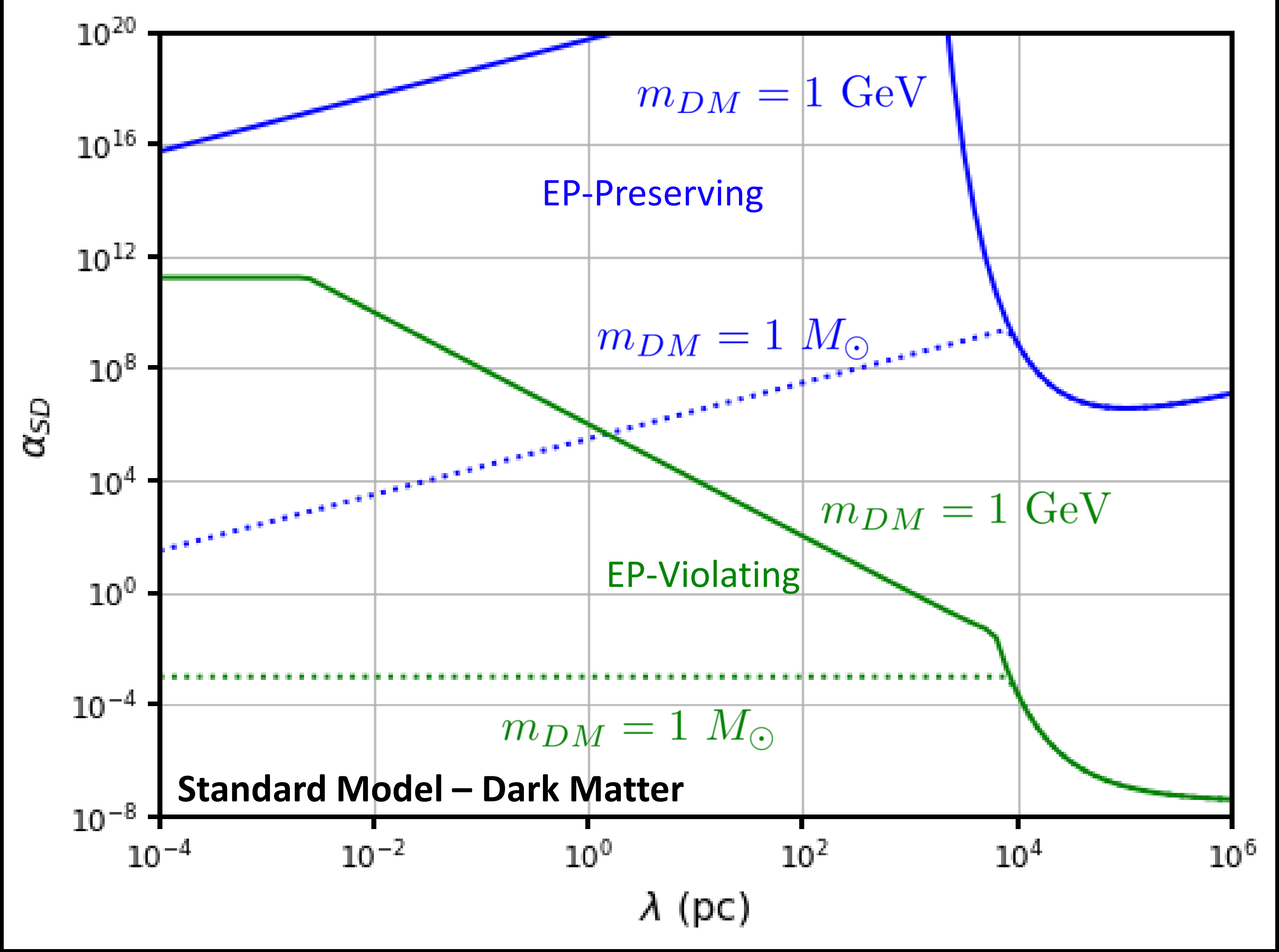
Species-dependent factors

- SM matter can’t be net-neutral (for this work)
- DM could be net-neutral or not

Existing constraints on long-range DM-SM interactions

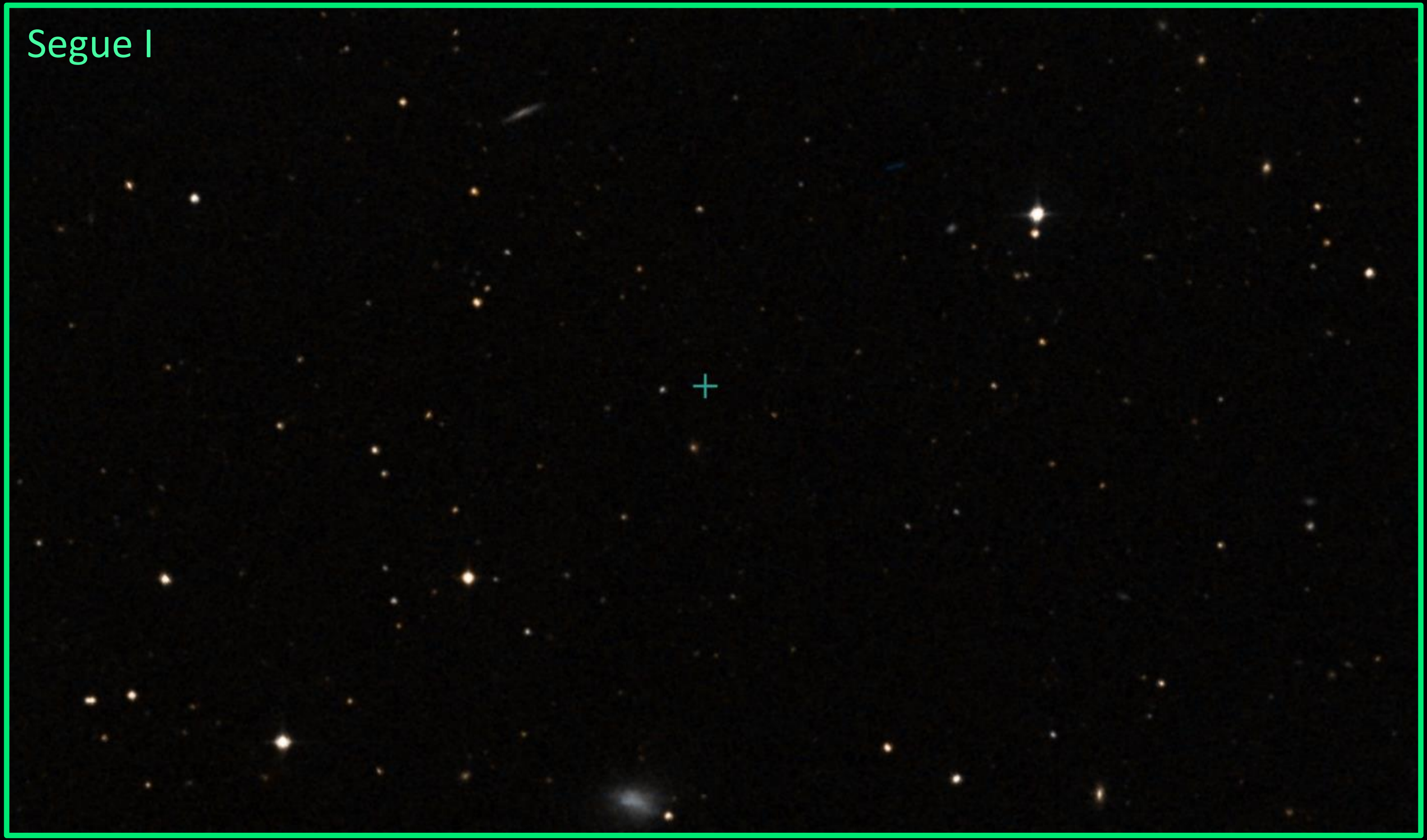
Various bounds:

- Torsion balances
- MICROSCOPE
- Bullet cluster transparency
- Bullet cluster collision velocity
- Separation of stellar streams
- …



hep-ph/0307284; *Prog. Part. Nucl. Phys.* **62** (2009) 102-134
gr-qc/2209.15487
astro-ph.CO/2207.10638
astro-ph/0606566; astro-ph/0608095; astro-ph.GA/0902.3452
astro-ph/0309303

Ultrafaint dwarfs are excellent laboratories for SM-DM interactions



From SIMBAD and DSS: http://simbad.u-strasbg.fr/simbad/sim-id?Ident=%403785419&Name=NAME%20Segue%201&submit=submit

Ultrafaint dwarfs are excellent laboratories for SM-DM interactions

UFDG Name	M_V (mag)	L_V ($L_\odot$)	$r_{h,\star}$ (pc)	$\sigma_\star$ (km s^{-1})
Draco II	$-0.8^{+0.4}_{-1.0}$	$1.8^{+1.2}_{-0.7} \times 10^2$	$19.0^{+4.5}_{-2.6}$	<5.9 (95 per cent CL)[a]
Segue I	-1.30 ± 0.73	$2.8^{+2.7}_{-1.4} \times 10^2$	24.2 ± 2.8	$3.7^{+1.4}_{-1.1}$
Tucana III	-1.3 ± 0.2	$2.8^{+0.6}_{-0.5} \times 10^2$	34 ± 8	<1.2 (90 per cent CL)[a]
Triangulum II	-1.8 ± 0.5	$4.5^{+2.6}_{-1.7} \times 10^2$	17.4 ± 4.3	<3.4 (90 per cent CL)[a]
Segue II	-1.86 ± 0.88	$4.7^{+6.9}_{-1.6} \times 10^2$	38.3 ± 2.8	<2.6 (95 per cent CL)[a]
Carina III	-2.4 ± 0.2	$7.8^{+1.6}_{-1.3} \times 10^2$	30 ± 9	$5.6^{+4.3}_{-2.1}$ [a]
Willman I	-2.53 ± 0.74	$8.8^{+8.6}_{-4.3} \times 10^2$	27.7 ± 2.4	4.0 ± 0.8
Boötes II	-2.94 ± 0.74	$1.3^{+1.3}_{-0.6} \times 10^3$	38.7 ± 5.1	10.5 ± 7.4
Grus I	-3.47 ± 0.59	$2.1^{+1.5}_{-0.9} \times 10^3$	28.3 ± 23.0	$2.9^{+6.9}_{-2.1}$
Horologium I	-3.55 ± 0.56	$2.2^{+1.5}_{-0.9} \times 10^3$	36.5 ± 7.1	$4.9^{+2.8}_{-0.9}$
Reticulum II	-3.88 ± 0.38	$3.0^{+1.3}_{-0.9} \times 10^3$	48.2 ± 1.7	3.3 ± 0.7
Tucana II	-3.9 ± 0.2	$3.1^{+0.6} \times 10^3$	120 ± 30	$8.6^{+4.4}$

Age $\gtrsim 10$ Gyr

Density $\sim 1\ M_\odot/\mathrm{pc}^3$

https://web.archive.org/web/20210223225516id_/https://www.zora.uzh.ch/id/eprint/191094/1/staa170.pdf

Dynamical friction is how galaxies gravitationally thermalize

Heat transfer per unit time and volume
(from "hot" stars to "cold" dark matter)

$$m_* v_*^2 \gg m_{\rm DM} v_{\rm DM}^2$$

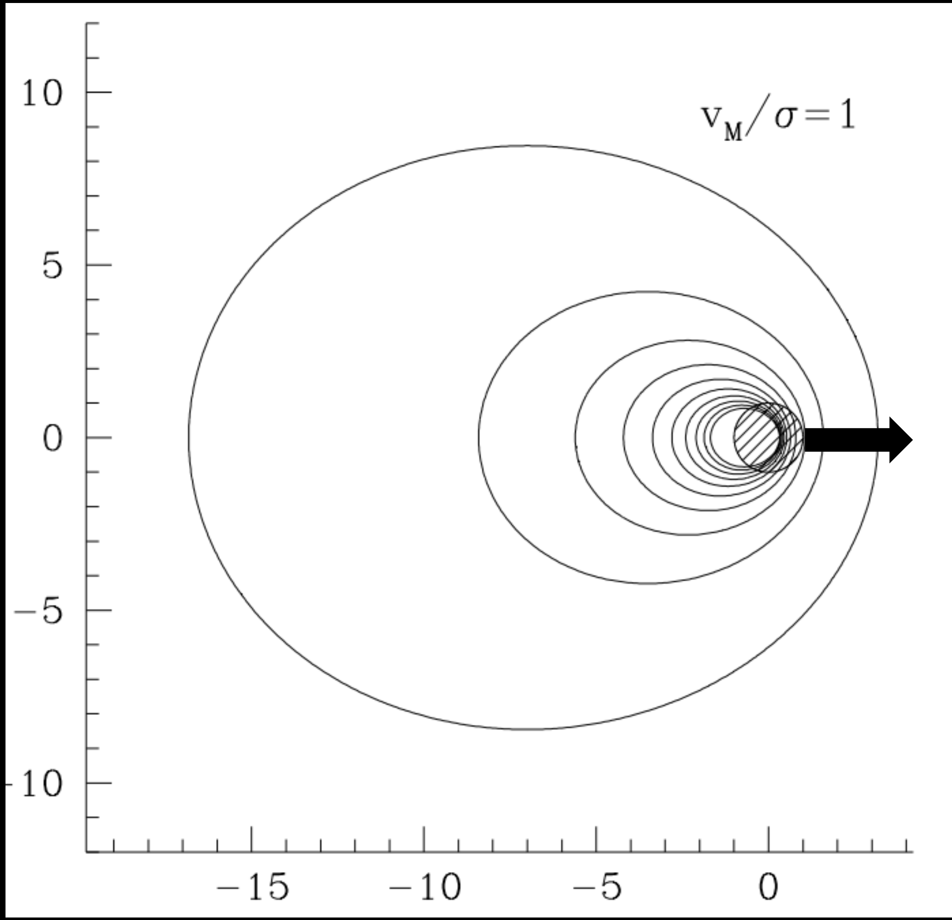
Effects of e.g. force range

$$\frac{d^2Q}{dV\,dt} \sim G^2 M_* \rho_* \rho_{DM} \frac{v_*^2}{\left(v_*^2 + v_{DM}^2\right)^{3/2}} \ln\left(\ldots\right)$$

Typical star mass

Mass Density (of Stars/Dark Matter)

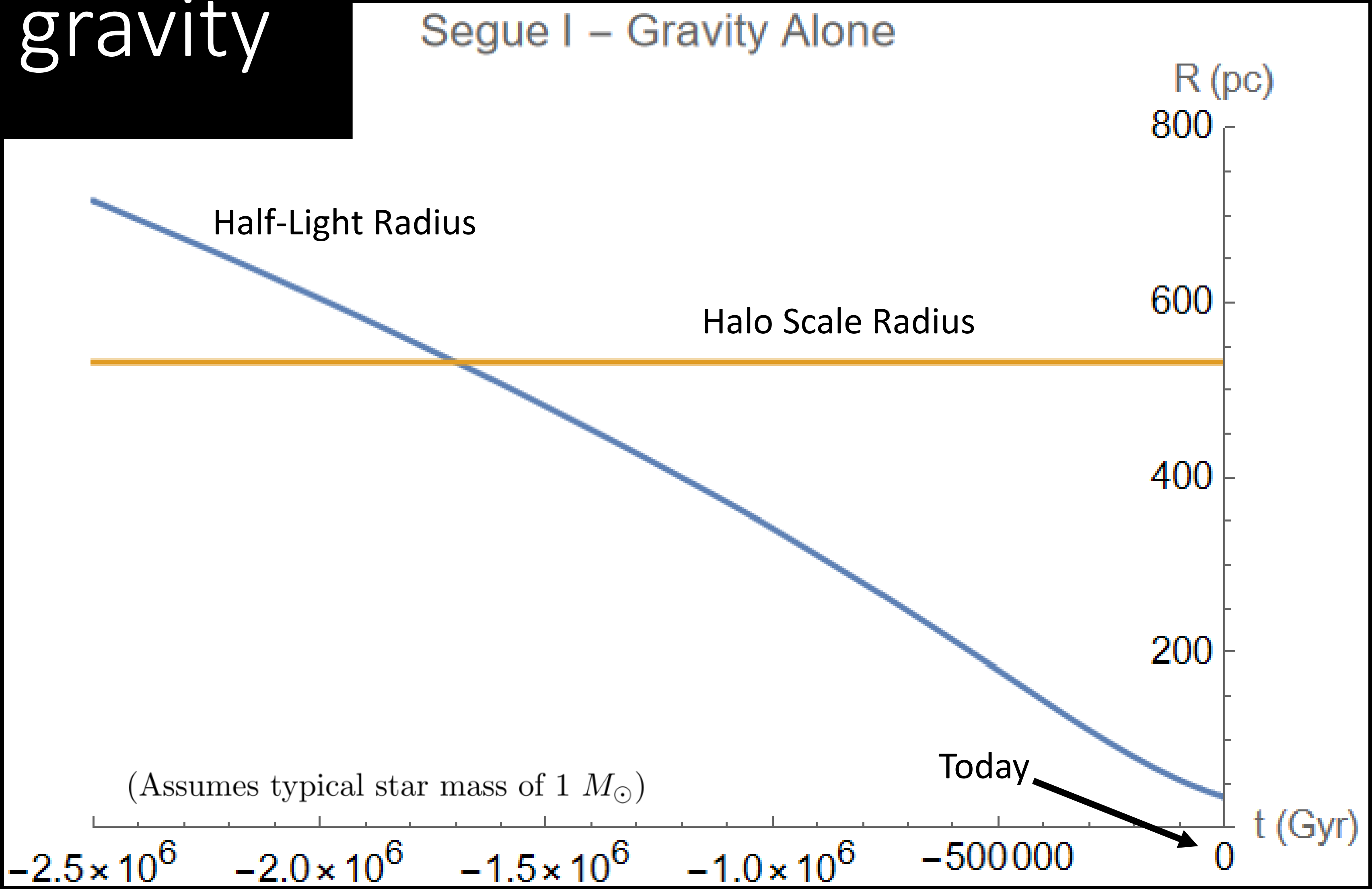
Velocity (of Stars/Dark Matter)



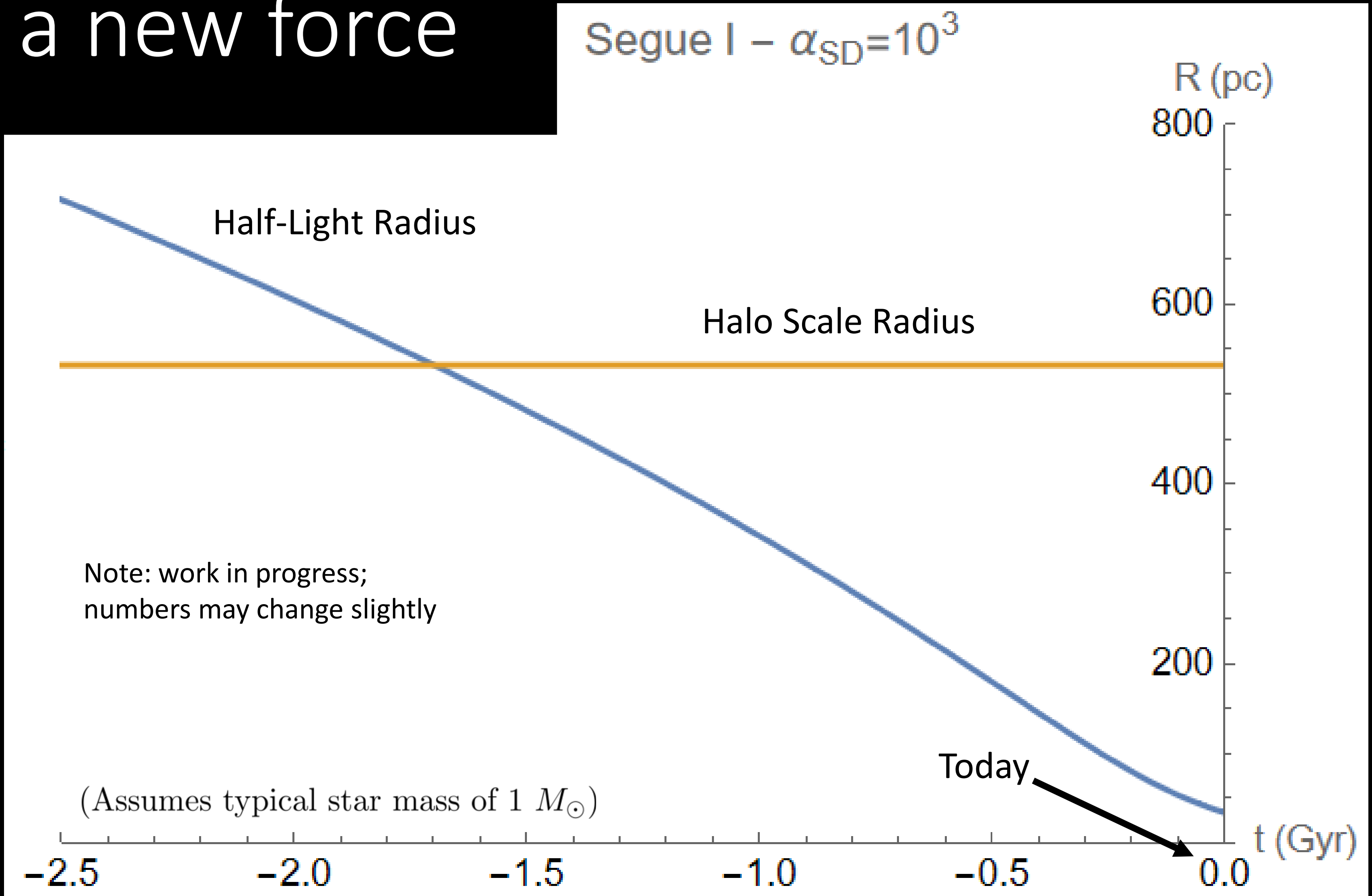
Binney, James and Tremaine, Scott. *Galactic Dynamics: Second Edition*, Princeton: Princeton University Press, 2008. https://doi.org/10.1515/9781400828722

Dynamical Friction in Ultrafaint Dwarf Galaxies

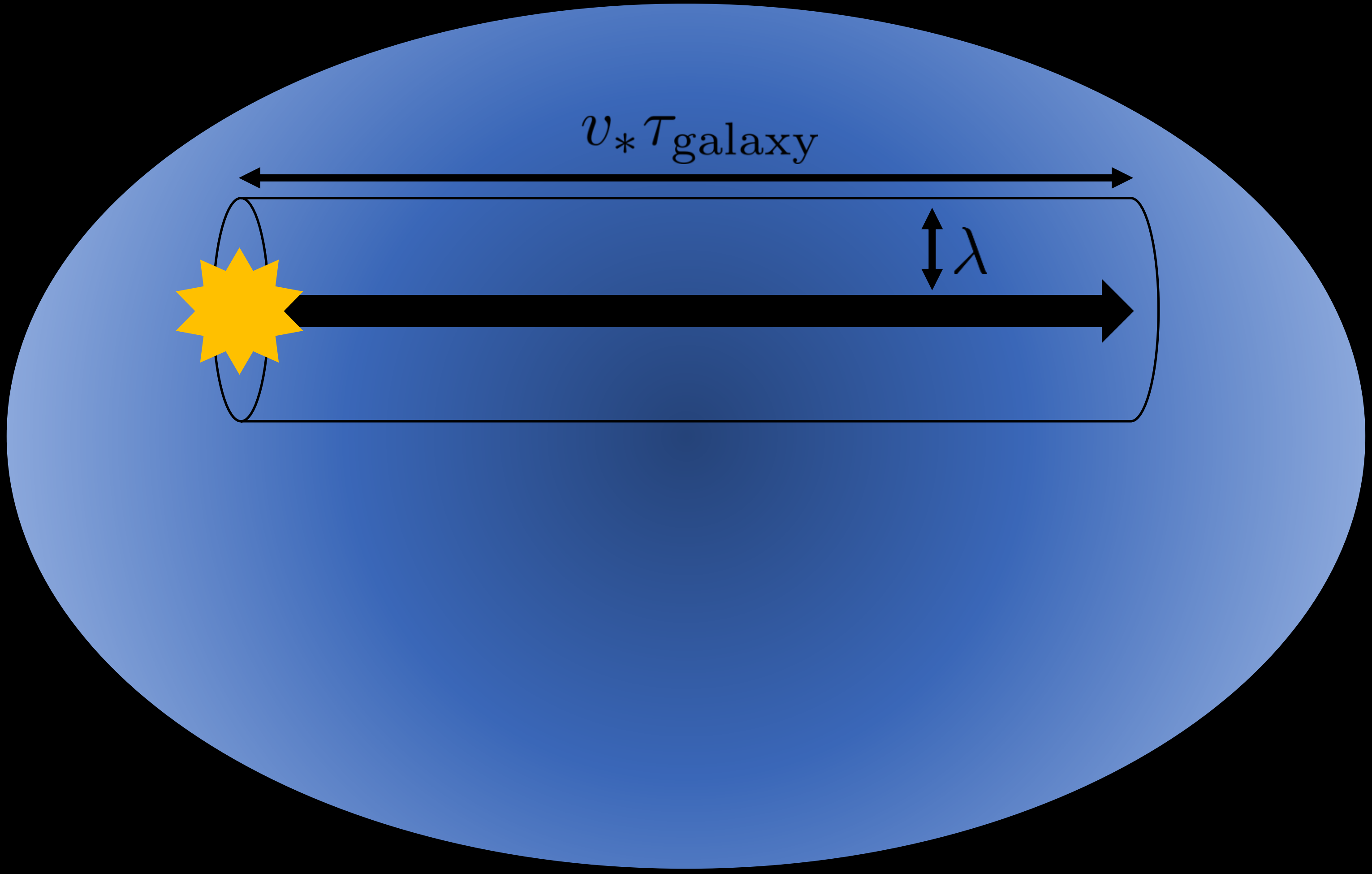
Stellar evolution due to dynamical friction from gravity



Stellar evolution due to dynamical friction from a new force



Forces with range less than O(1 mpc) don't affect stellar evolution significantly



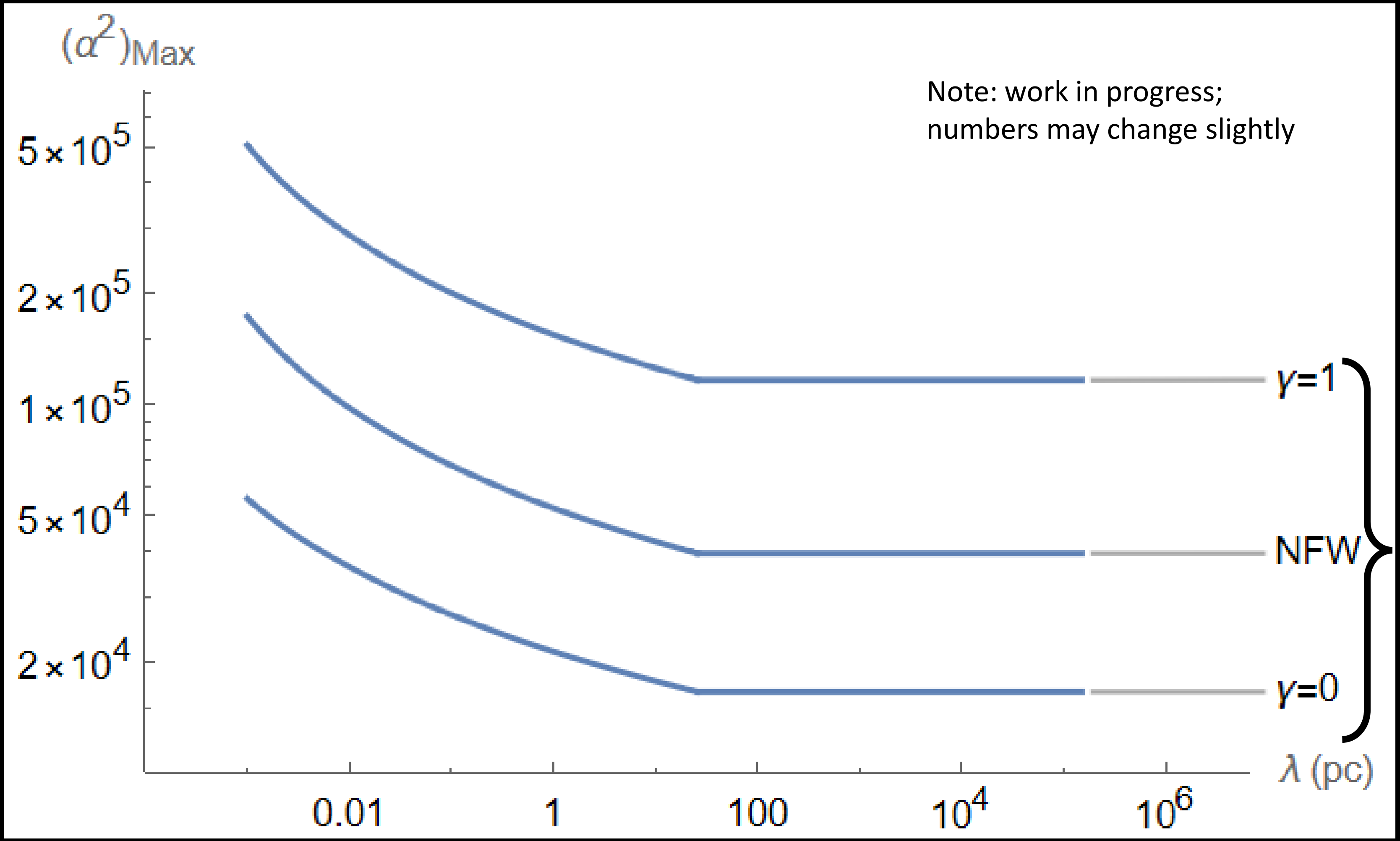
$$q_{\rm transfer} \lesssim m_{DM} v_{\rm rel}$$

$\Downarrow$

$$\pi \lambda^2 v_{\rm rel} \tau_{\rm galaxy} \rho_{DM} \gtrsim m_*$$

for order-1 effects

Conservative assumptions about initial conditions then constrain new SM-DM forces

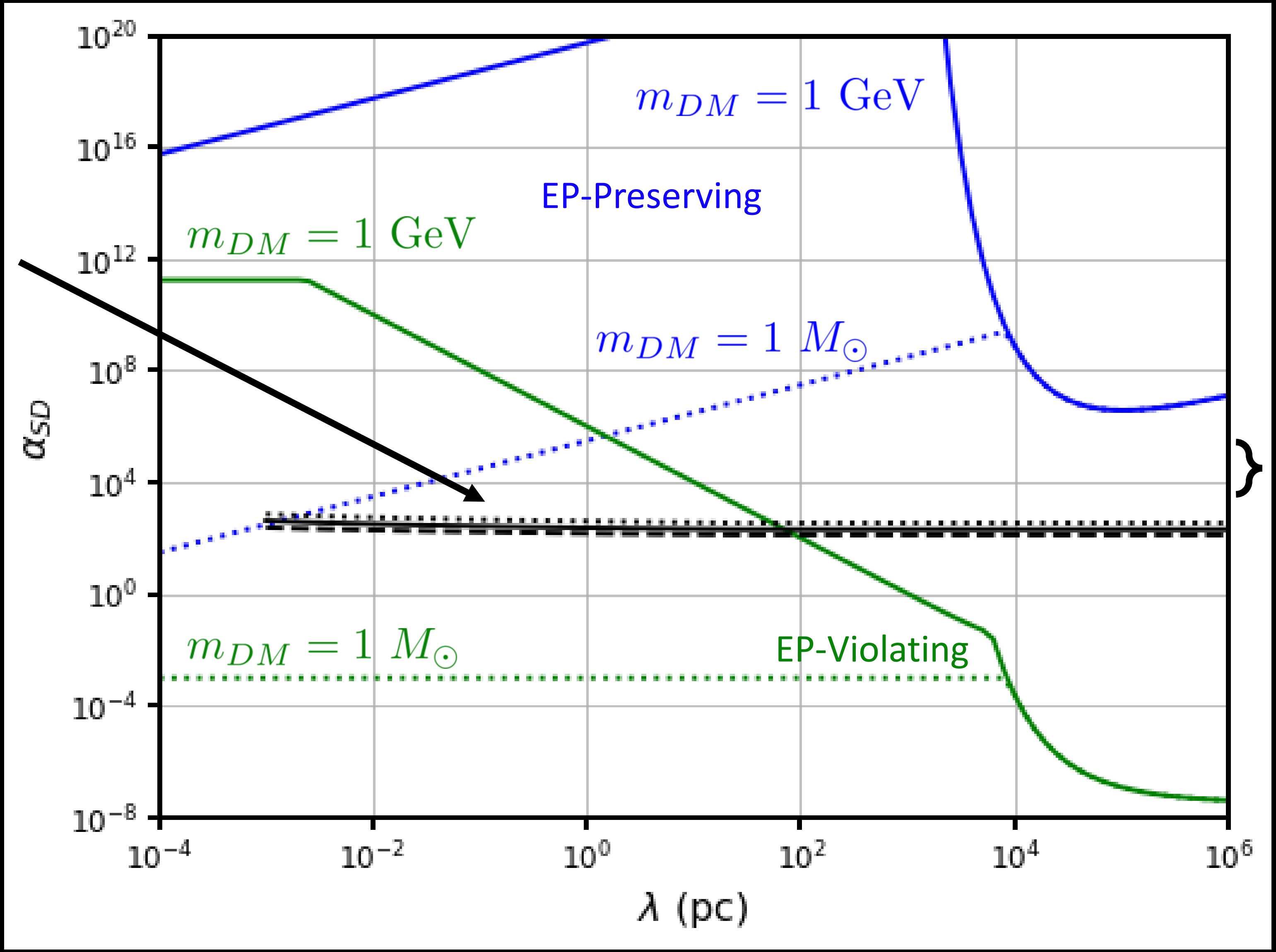


Halo Profiles

Summary

Our constraints from dynamical friction

(Assuming no Debye screening; otherwise parameter space is more complicated)



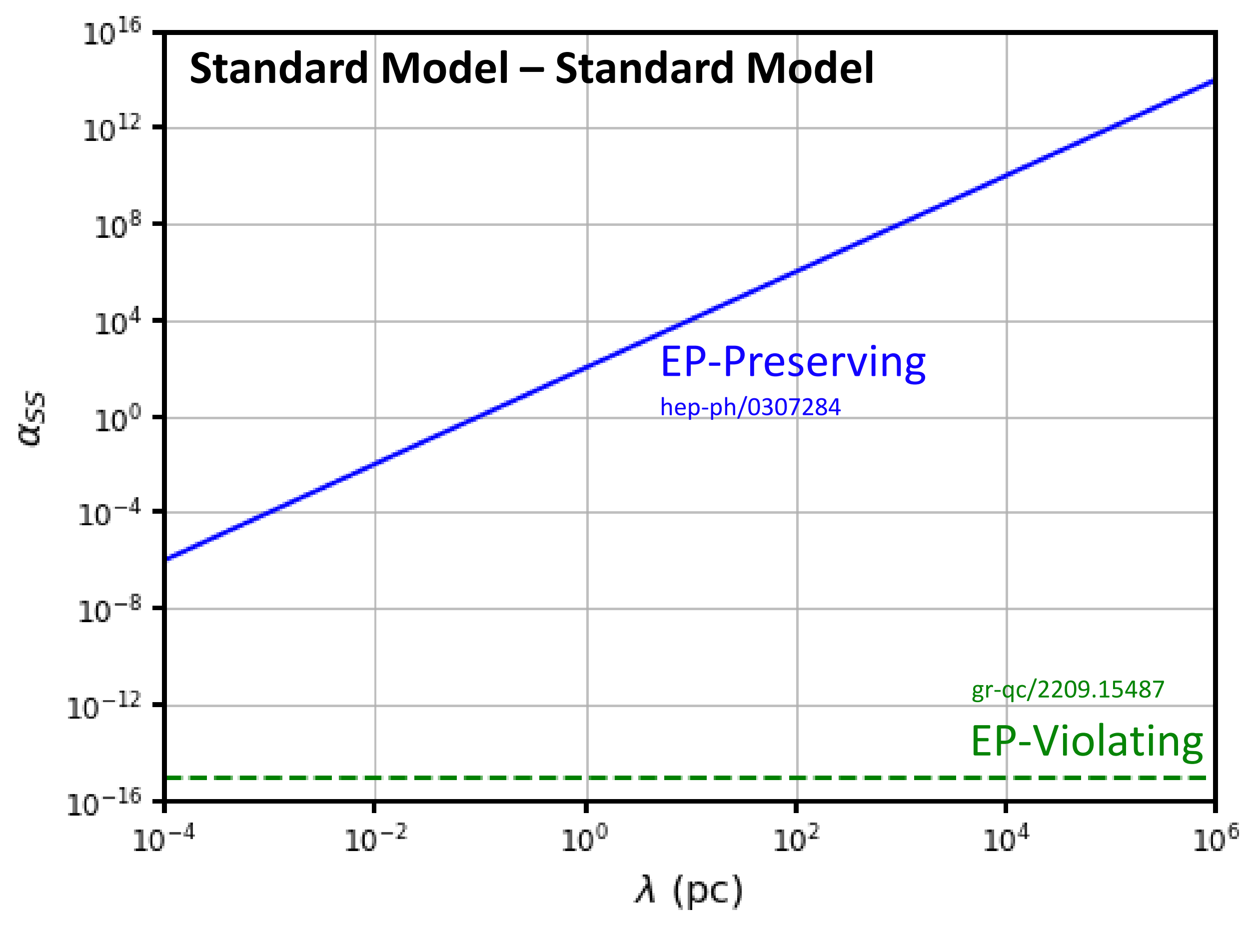
} Halo Profiles

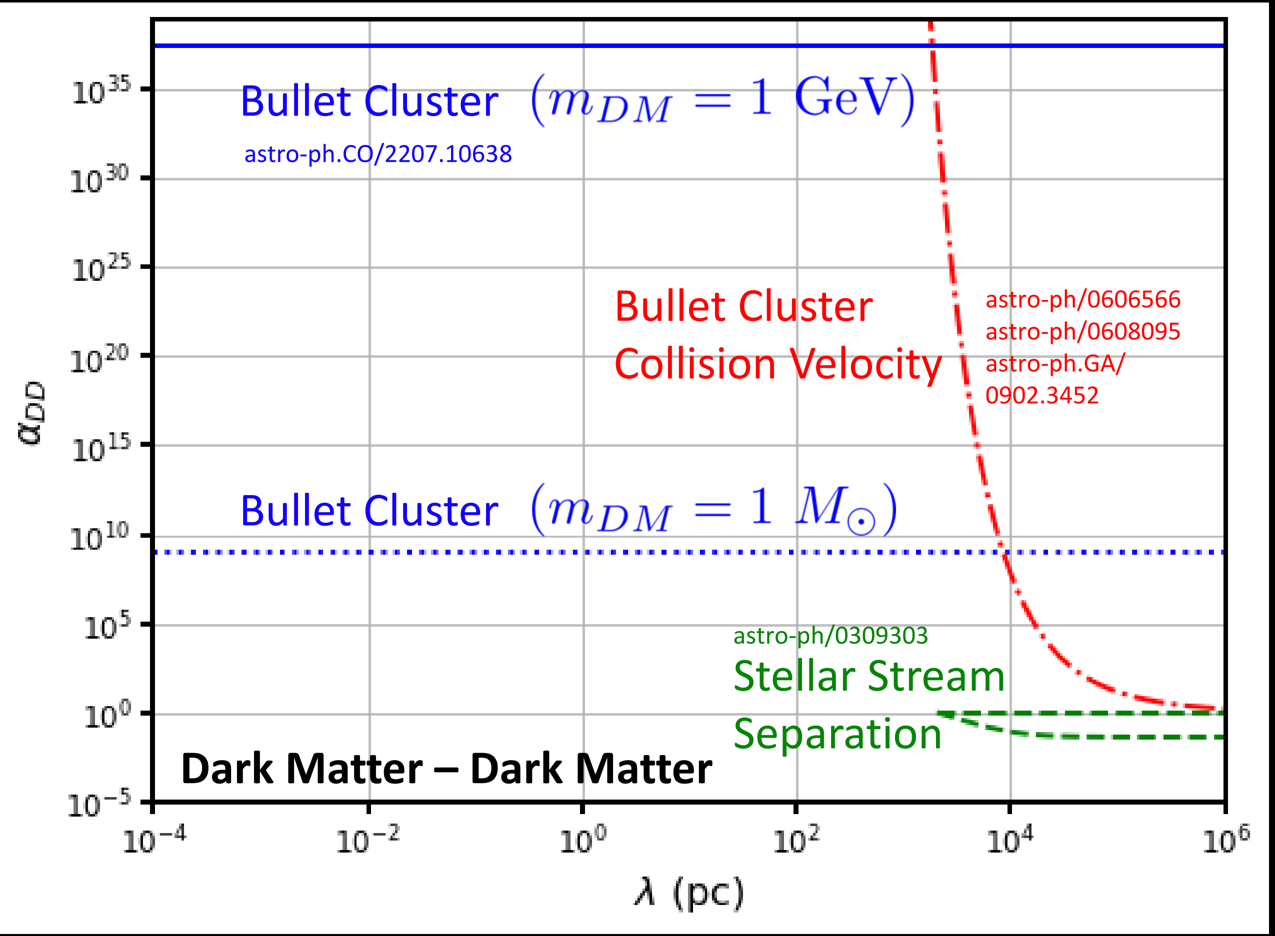
Note: work in progress; numbers may change slightly

Questions?

Backup Slides

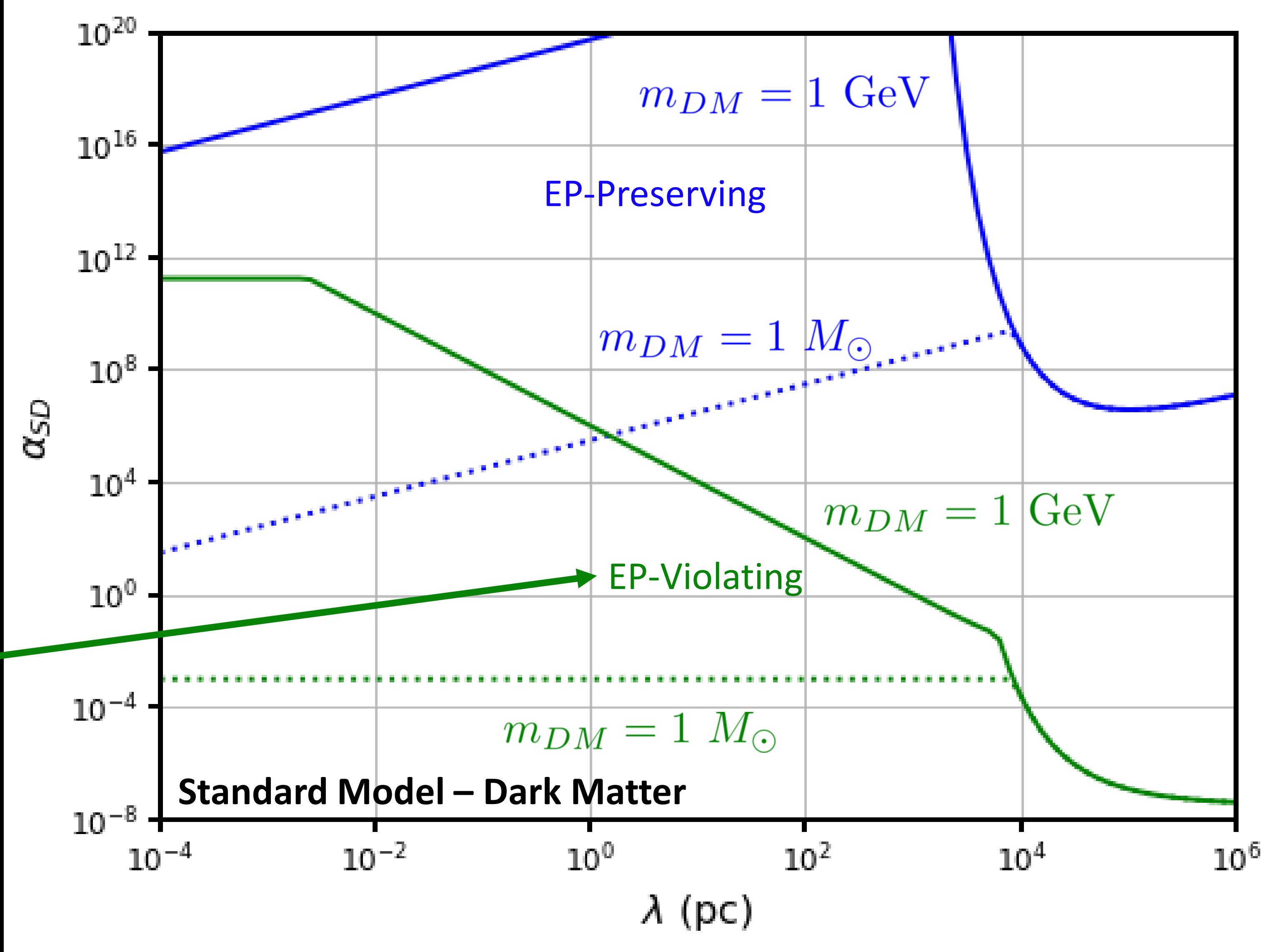
Existing constraints on long-range DM-SM interactions





Existing constraints on long-range DM-SM interactions

$$\alpha_{SD} \leq \sqrt{\alpha_{SS}\alpha_{DD}}$$



Also includes a direct constraint on α_{SD} from looking for MW-center-directed EP violation

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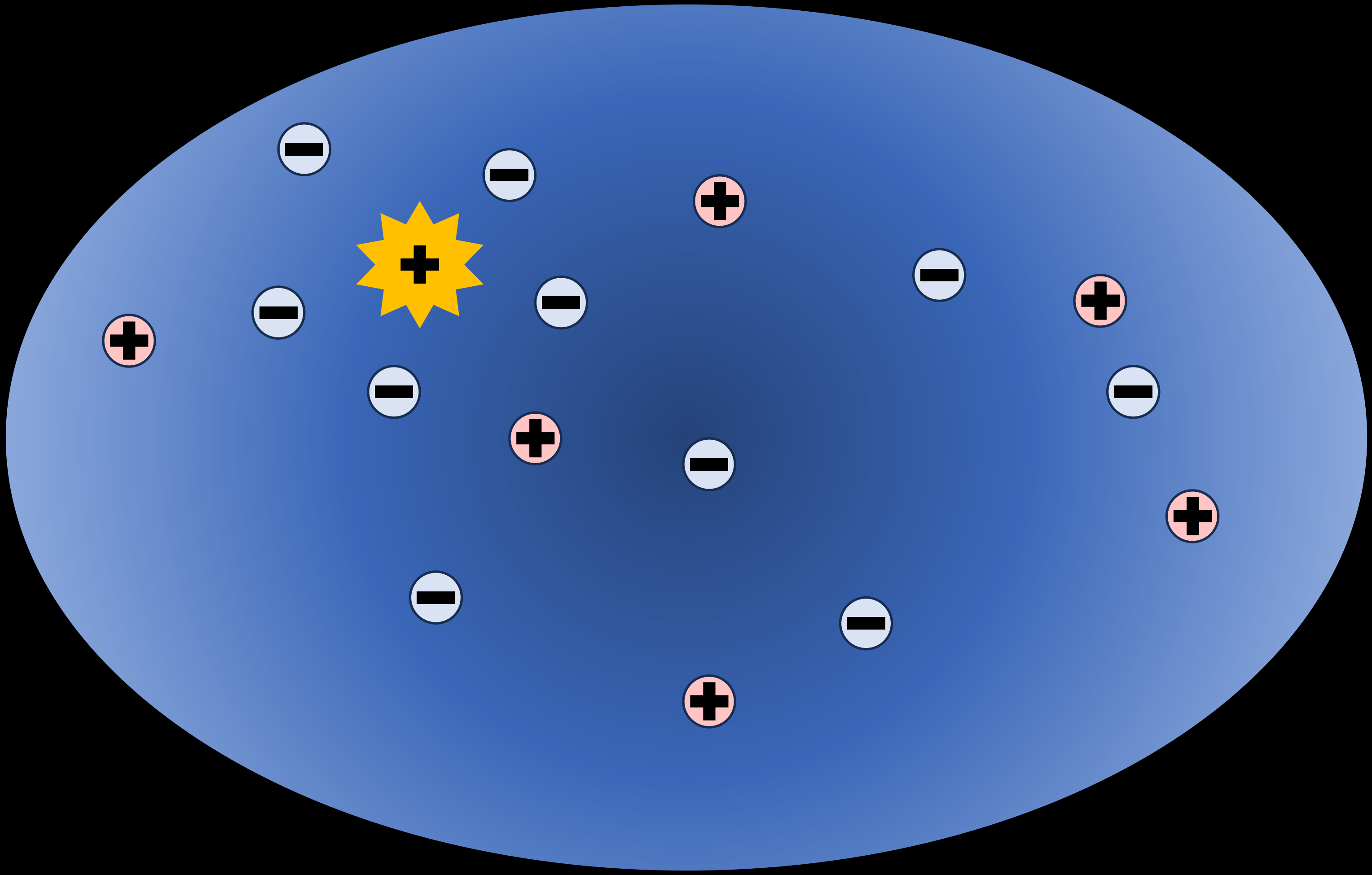
If dark matter has mixed charge signs, Debye screening limits the new force's range



$$\lambda_D \sim \sqrt{\frac{v_{DM}^2}{4\pi\alpha_{DD} G \rho_{DM}}}$$

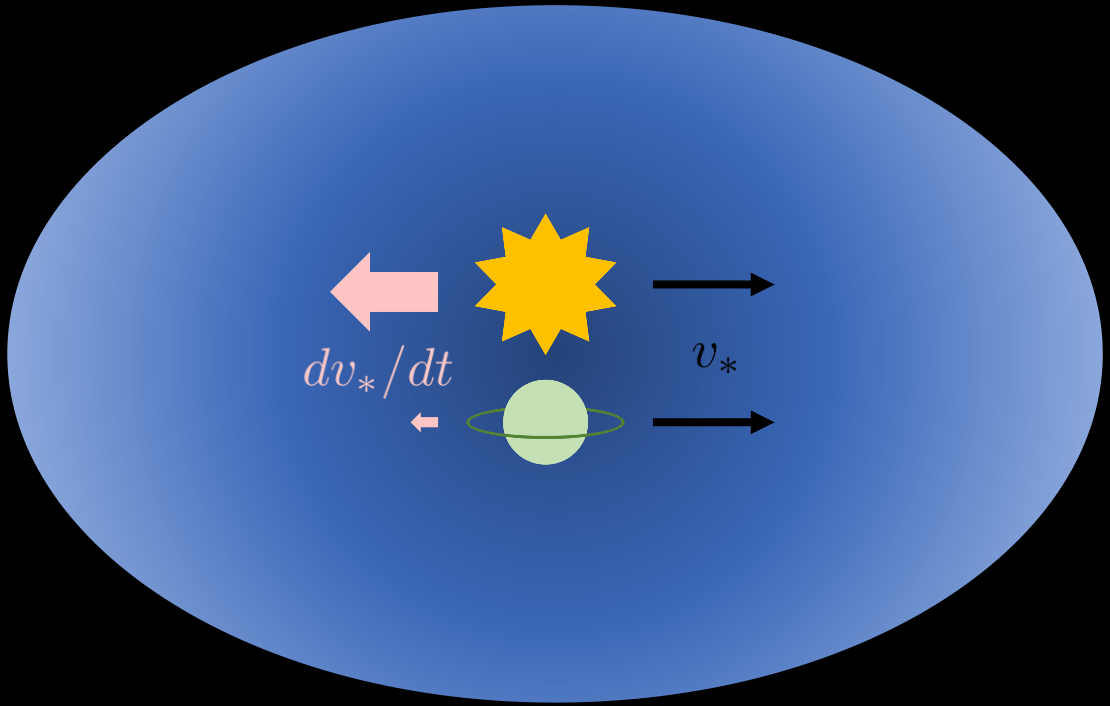
$$\sim 1 \text{ mpc} \left(\frac{\alpha_{DD}}{10^{10}}\right)^{-1/2}$$

Dynamical friction also leads to anomalous acceleration of planets and satellites

Acceleration from dynamical friction

Mass of star (or planet, etc.)

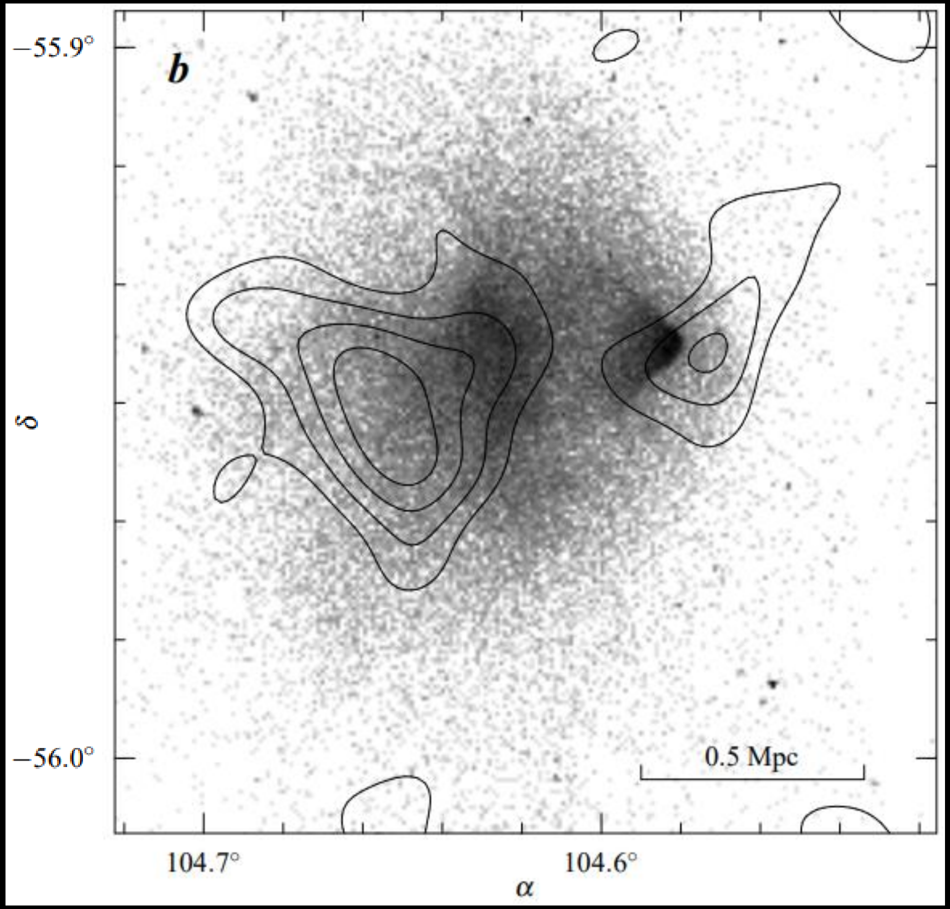
$$\frac{dv_*}{dt} \sim -G^2 M_* \rho_* \rho_{DM} v_* \left(\frac{v_*}{v_{DM}}\right)^3 \ln(\ldots)$$



Differential acceleration between the Sun and a satellite could give similar limits to UFDs

gr-qc/1508.06273

At very long ranges, the collision velocity of the Bullet Cluster gives a stronger constraint



Speed at collision from measured mass:

$$4400 \pm 700 \text{ km/s}$$

Speed at collision from gas shock:

$$4500^{+1100}_{-800} \text{ km/s}$$

Forces stronger than gravity with ranges of at least 150 kpc would increase collision speed